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SIMULATION EXPERIMENTS USING A FINE-GRID HYDRODYNAMIC MODEL OF THE MEDITERRANEAN SEA

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SIMULATION EXPERIMENTS USING A FINE-GRID HYDRODYNAMIC MODEL OF THE MEDITERRANEAN SEA

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ABSTRACT

Simulations have been performed using a primitive equation, sigma-coordinate, hydrodynamic model of the Mediterranean Sea. The model uses a climatological temperature-salinity field on a grid with a spacing of 5-12 km in the horizontal. Simulations indicate that the model does a good job in reproducing the surface height amplitude and phase of the M_2 tide. The semi-major axes of the model M_2 current ellipses in the Strait of Gibraltar were approximately 50% smaller than the observed current ellipses. This is a result of the data base used to generate the model bathymetry, which has depths in the vicinity of the sill of the Strait of Gibraltar (~300 m) which are about two times too deep (~550 m).

Additional simulations show current fluctuations that may be the result of a) the interaction of the climatological density field with the model bathymetry to trigger strong baroclinic modes or b) problems associated with the application of sigma-coordinates over steep bathymetry. When the model bathymetry was smoothed, the current fluctuations were eliminated. However, it is unclear if the smoothing eliminated a bathymetry/sigma-coordinate problem or simply eliminated the shelf slopes and breaks which are responsible for the generation of the baroclinic currents.

1. INTRODUCTION

The importance of the Mediterranean Sea is not only in terms of its strategic location but also in terms of the physical processes that occur in the Mediterranean. These processes include coastal, shelf, and deep water phenomena. Wind forcing and buoyancy fluxes force a wide range of processes ranging from basin scales to the scales of coastal jets. In fact, most of the processes that are fundamental to the circulation in the world's oceans can be found within the Mediterranean. This includes the production of deep bottom waters.

The Mediterranean has only a limited connection with the rest of the world's oceans. However, because of the salinity differences with respect to the Mediterranean and the Atlantic Ocean, the Mediterranean can still play an influential role in the thermohaline circulation of the hydrosphere. Thus, it is of considerable interest to be able to model the Mediterranean, its coastal regions, shelves, and deep water as well as the connection to the Atlantic. Such a modeling capability allows us to better understand particular processes, including near-shore, shelf, and deep water interactions.

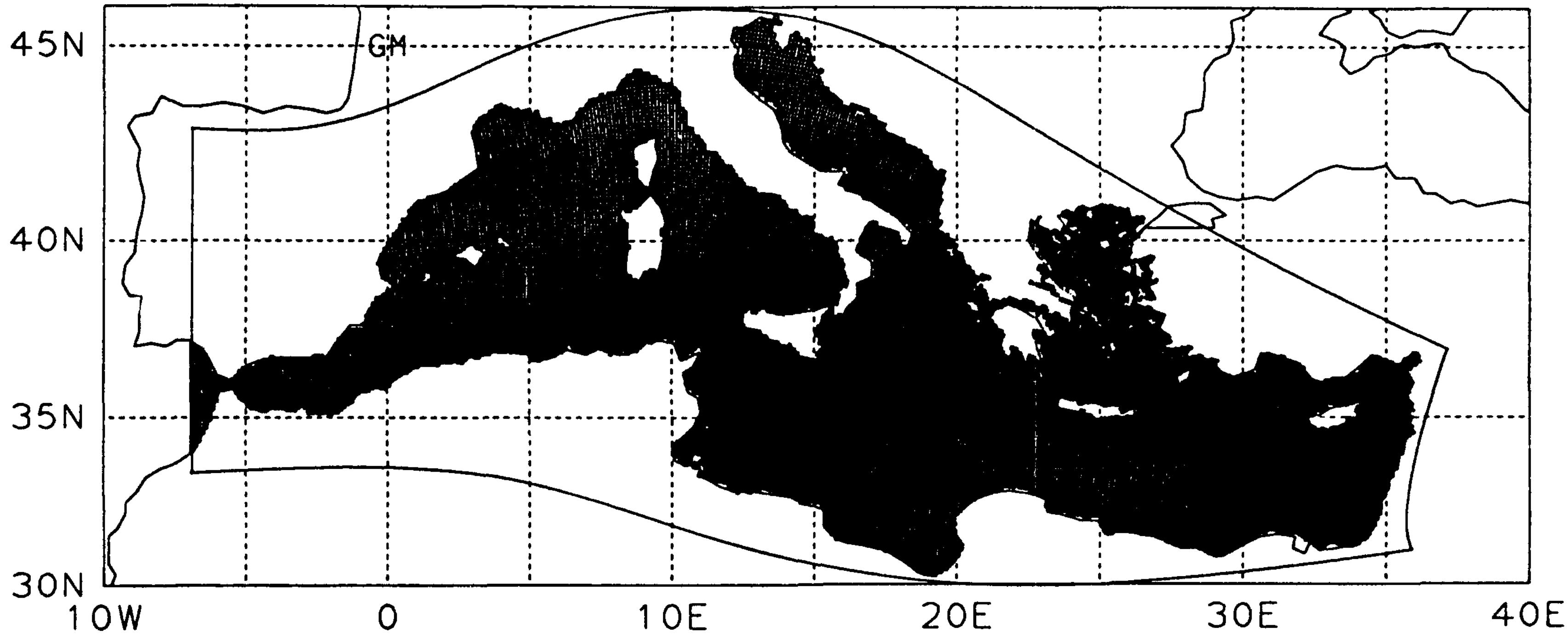

Fig. 1. Model domain for the Mediterranean Sea hydrodynamic model.

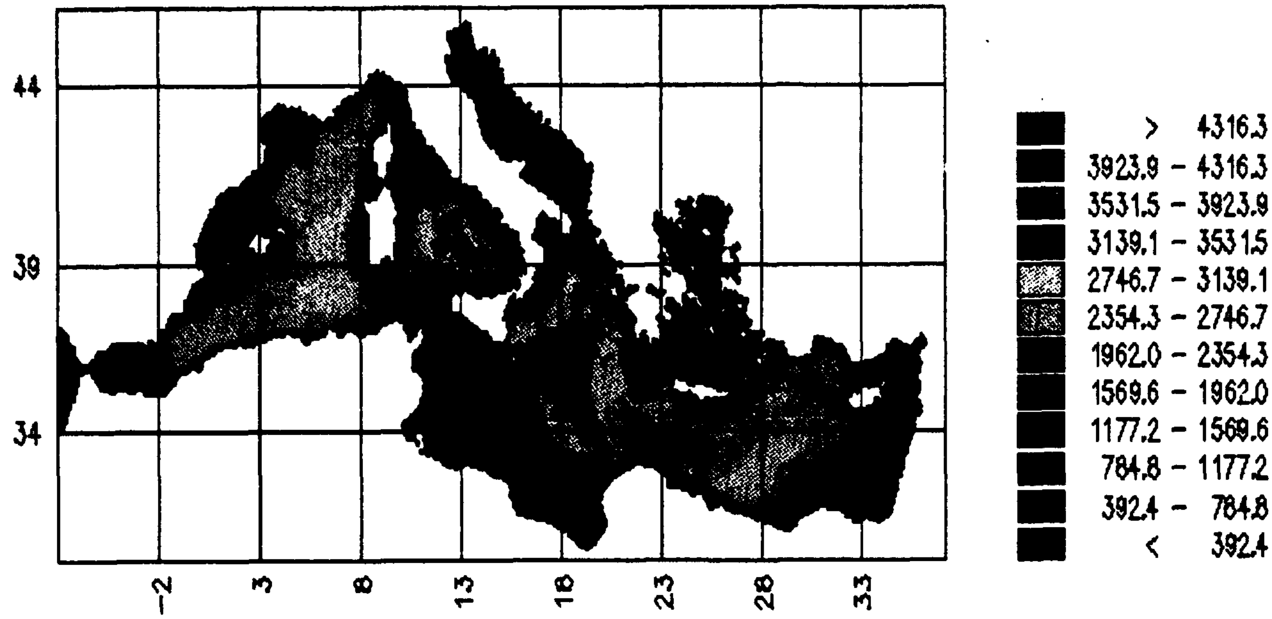

Fig. 2. Color-coded chart of the bathymetry used by the model. The color code to the right of the figure is depth in meters.

In this paper, we describe the adaptation of a primitive equation, sigma-coordinate, hydrodynamic model to a Mediterranean Sea grid with a spacing of 5-12 km in the horizontal. Simulations have been performed to determine the basic characteristics of the model based upon the grid, an appropriate bathymetry (depths of 2 to 4500 m), and a climatological temperature-salinity field. Diagnostic and prognostic simulations were performed, and the resulting current characteristics were studied, especially those in the coastal regions of the Mediterranean. In general, the prognostic simulations show current fluctuations that are similar to those we would expect as the result of internal modes generated by flow over a shelf slope and break (Baines, 1982). Curiously, many of these baroclinic modes have strong semidiurnal oscillations. Since the diagnostic simulations do not result in these current variations, the model results indicate that the climatological density field is interacting with the model bathymetry to trigger these strong baroclinic currents. However, there is the possibility that problems associated with the application of sigma-coordinates over steep bathymetry is the cause of these baroclinic currents. When the model bathymetry is smoothed, the current fluctuations are eliminated. However, we are unsure if the smoothing eliminates the problem of bathymetry and sigma-coordinates or if it simply eliminates the shelf slopes and breaks which are responsible for the generation of internal modes to begin with (Baines, 1982).

Simulations were also performed to determine how well the model could reproduce the M_2 tides in the Mediterranean Sea. The results indicate that the model does a good job in reproducing the barotropic tide. The semi-major axes of the model M_2 current ellipses in the Strait of Gibraltar had the correct phase but were approximately 50% smaller than the observed M_2 tidal currents. The differences in amplitude were traced to the data base used to generate the model bathymetry. The data base bathymetry in the vicinity of the sill of the Strait of Gibraltar is about two times too deep.

2. MODEL CHARACTERISTICS

Model Grid

The hydrodynamic model used in this work is the sigma-coordinate model of Blumberg and Mellor (1987). The model, often referred to as the Princeton model, is based on the primitive equations for momentum,

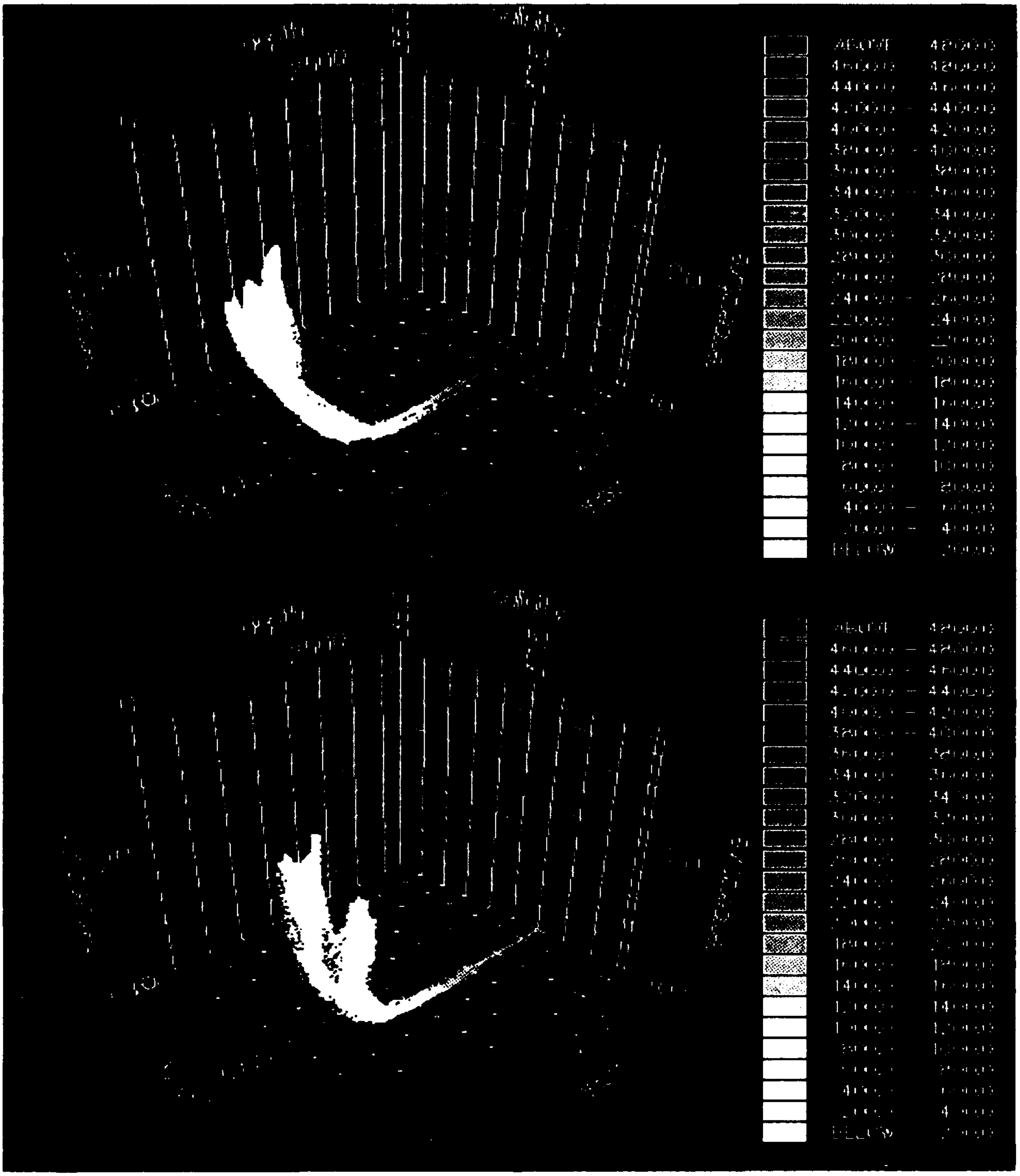

Fig. 3. Potential temperature and salinity relationships versus depth for the western (top) and eastern (bottom) Mediterranean Sea basins as divided by the Strait of Sicily.

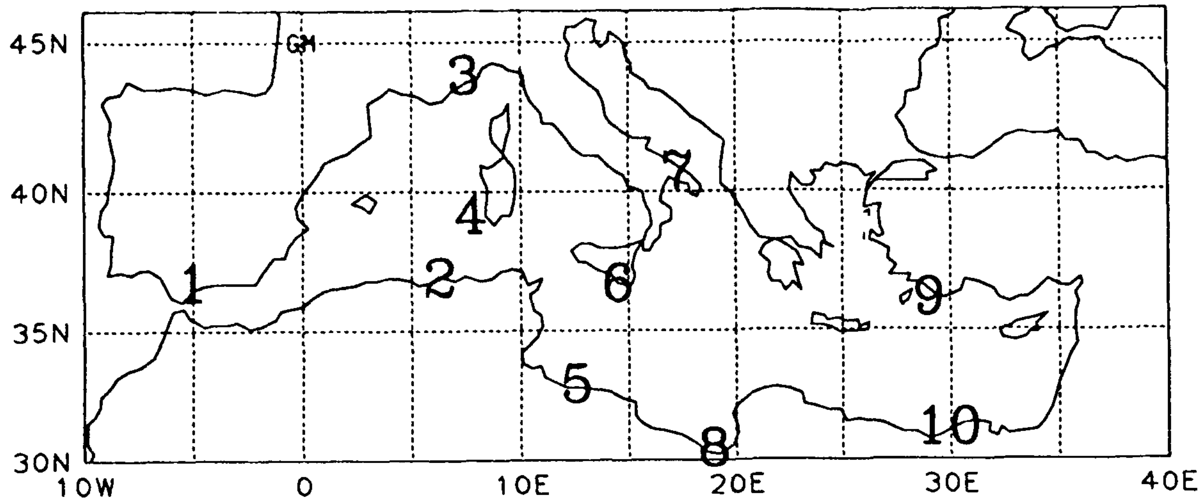

Fig. 4. Stations for which model-predicted currents or surface height variations are presented in subsequent figures.

salt, and heat. Sub-grid scale turbulence is specified using the schemes of Mellor and Yamada (1982) in the vertical and Smagorinsky (1963) in the horizontal. For additional information on the model, the reader is referred to Blumberg and Mellor (1987).

The model uses a curvilinear, orthogonal grid in the horizontal and a bottom-following sigma-coordinate grid in the vertical. The grid mesh was chosen based on the reported baroclinic radius of deformation in the eastern Mediterranean of 10-12 km. Grid spacing in the horizontal for the Mediterranean Sea model ranges from 7.1 to 11.4 km in the "x" direction (nominally east-west) and 4.4 to 12.3 km in the "y" direction (nominally north-south). Thus, we would expect the model to be capable of resolving average sized and larger flow features in the Mediterranean. The model domain (Fig. 1) consists of 441 x 141 grid cells in the horizontal. The time step is 15 s for the barotropic mode and 600 s for the baroclinic mode. The forcing for all simulations were ramped up over 1.5 inertial periods.

The model has 15 sigma levels in the vertical, allowing for 14 active layers. The distribution of layers of the depth for any given grid cell is given in Table 1. As can be seen, the finer vertical resolution is concentrated at the surface of the water column.

Bathymetry

The bathymetry used by the model (Fig. 2) is based on a 2"x2" data base developed by the Naval Oceanographic Office (NAVOCEANO). The NAVOCEANO data base represents average depths based on contours of depth at 200 m intervals (i.e., 0 m, 200 m, 400 m, etc.). As such, we cannot expect depth variations over the shelf to be very accurate. Moreover, sill depths may not be well represented. For example, the sill depth at the Strait of Gibraltar is only 300 m deep, but the 300 m contour is not even included in the set of contours used to generate the NAVOCEANO 2"x2" bathymetry.

To generate the model bathymetry, all data from the 2"x2" data base that fell within a grid cell of the model were averaged to obtain the depth for the grid cell. This resulted in a model bathymetry that ranged from a minimum depth of 2 m to a maximum depth of 4500 m. In many cases, the bathymetry for a sigma-coordinate model is often smoothed to minimize problems associated with sigma-coordinates over steep topography (Haney, 1991). However, all but one of our simulations were performed without smoothing the bathymetry. Since one of our goals is the simulation of shelf and coast ' phenomena, we do not wish to eliminate bathymetric characteristics that are

Table 1. Layer distribution percentages of the depth of a grid cell for the Mediterranean Sea model.

Layer 1:	0-0.1953%
Layer 2:	0.1953-0.3906%
Layer 3:	0.3906-0.7813%
Layer 4:	0.7813-1.5625%
Layer 5:	1.5625-3.125%
Layer 6:	3.125-6.25%
Layer 7:	6.25-12.5%
Layer 8:	12.5-25%
Layer 9:	25-37.5%
Layer 10:	37.5-50%
Layer 11:	50-62.5%
Layer 12:	62.5-75%
Layer 13:	75-87.5%
Layer 14:	87.5-100%

important with respect to these flow fields. For example, it is known that the shelf break and the steepness of the shelf slope is critical in the generation of the baroclinic tidal currents (Baines, 1982). In addition, recent work has indicated that inertial oscillations, a dominant phenomena in most coastal regions, tend to have a maximum at the shelf break (R. O. Reid, personal communication). Thus, we chose not to smooth the model bathymetry.

TEMPERATURE AND SALINITY

The initial potential temperature and salinity (T-S) fields for the model were adapted from the 15'x15' annual climatological averages developed by the National Institute for Oceanography and Fisheries at Alexandria, Egypt. The Egyptian data were provided originally on a three-dimensional sigma-coordinate grid that was considerably coarser than that used in this study. These original data were interpolated to the 30 conventional levels in the vertical described by Levitus (1982) using a bivariate approach (Akima, 1978). Any conventional level whose z coordinate was beyond (above or below) the coarser-grid, sigma-coordinate z level was assigned the T-S values of the nearest sigma-coordinate level. Bivariate interpolation in the horizontal was then used to produce our own climatological fields of T and S with a horizontal resolution of 0.25° latitude x 0.25° longitude at each conventional level. These data were interpolated to the finer model grid used in this study and then checked to insure that the water column was stable at all grid cells. The T-S relationships versus depth for the western and eastern Mediterranean basins are shown in Fig. 3. The bottom waters of the two basins are quite distinct. In the deeper eastern Mediterranean, the climatological salinity ranges from 38.52 to 38.82^{0}/oo, and the potential temperature varies from 13.18 to 13.59°C. In the somewhat shallower western Mediterranean, the bottom water is slighty fresher (38.35 to 38.55^{0}/oo) and cooler (potential temperature of 12.63 to 13.14°C).

BOUNDARY CONDITIONS, BOTTOM FRICTION

The only open boundary in the model is in the Atlantic Ocean, some 200 km west of the Strait of Gibraltar. A longwave radiation condition was used for the vertically-averaged velocities at this boundary in the form of

$$U = - \eta \, (g/D)^{\frac{1}{2}} \qquad (1)$$

where U is the barotropic velocity perpendicular to the model boundary, η is the surface height anomaly of the boundary grid cell, g is the acceleration due to gravity, and D is the water depth.

A simple upwind advection scheme was used at the open boundary for temperature and salinity. When the flow was into the model domain, the climatological temperatures and salinities were advected into the model.

We also considered specifying the vertical structure of the currents at the open boundary in order to handle the baroclinic modes better at the boundary. We investigated the modified Orlanski boundary condition which uses the velocity in the grid cell adjacent to the boundary from a previous time step (Camerlengo and O'Brien, 1980). This essentially sets the propagation speed of the internal modes at all depths to the grid size divided by the internal time step of the model. At the western open boundary of the Mediterranean Sea model, this would mean a phase speed for the internal modes of 8-9 m/s. This is considered to be far too large, especially for the lower and upper layers of the water column. Simulation experiments

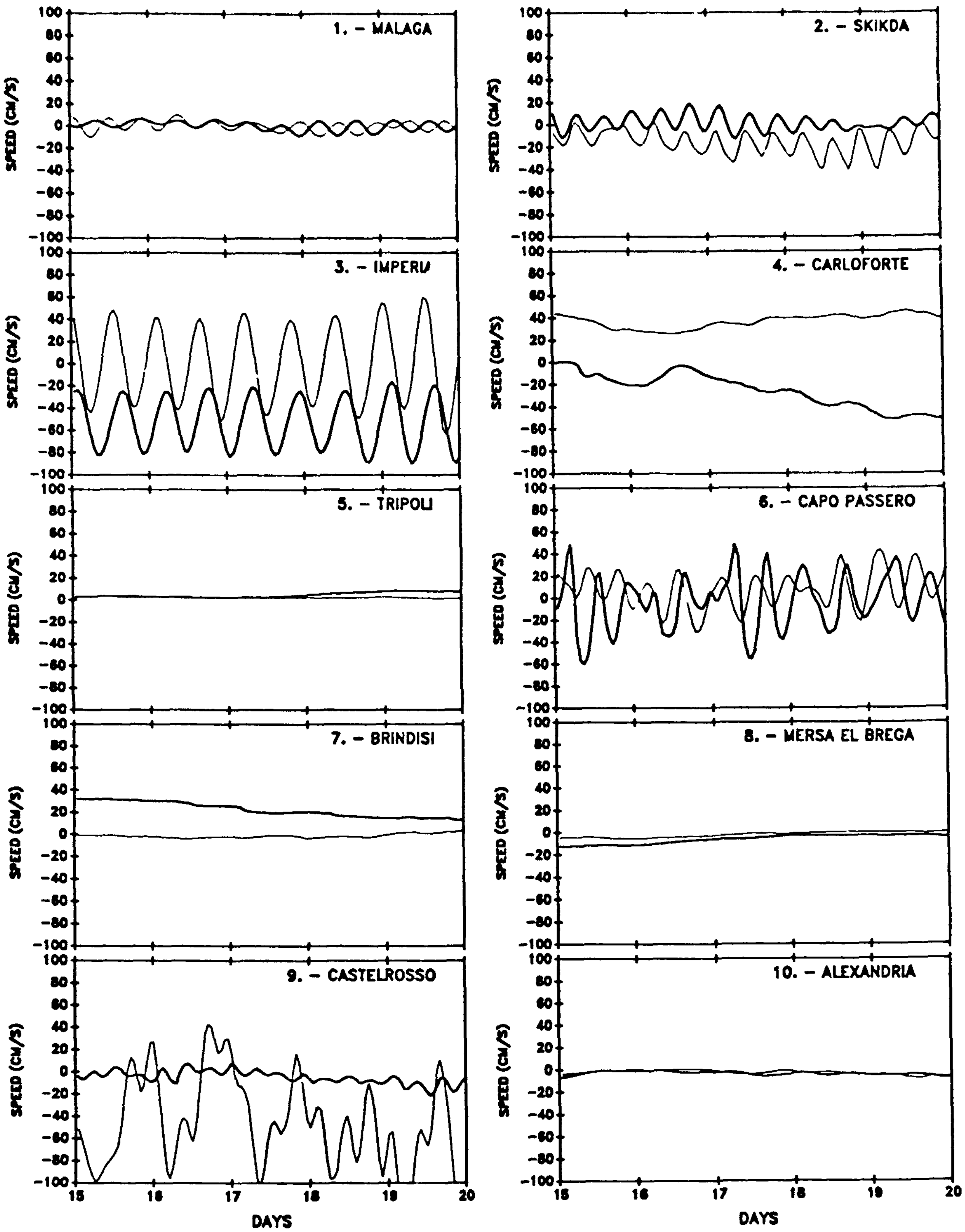

Fig. 5. Surface currents during the last 5 days of a 20 day prognostic simulation using the climatological temperatures and salinities. Darker lines are the x-directed currents, and lighter lines are the y-directed currents.

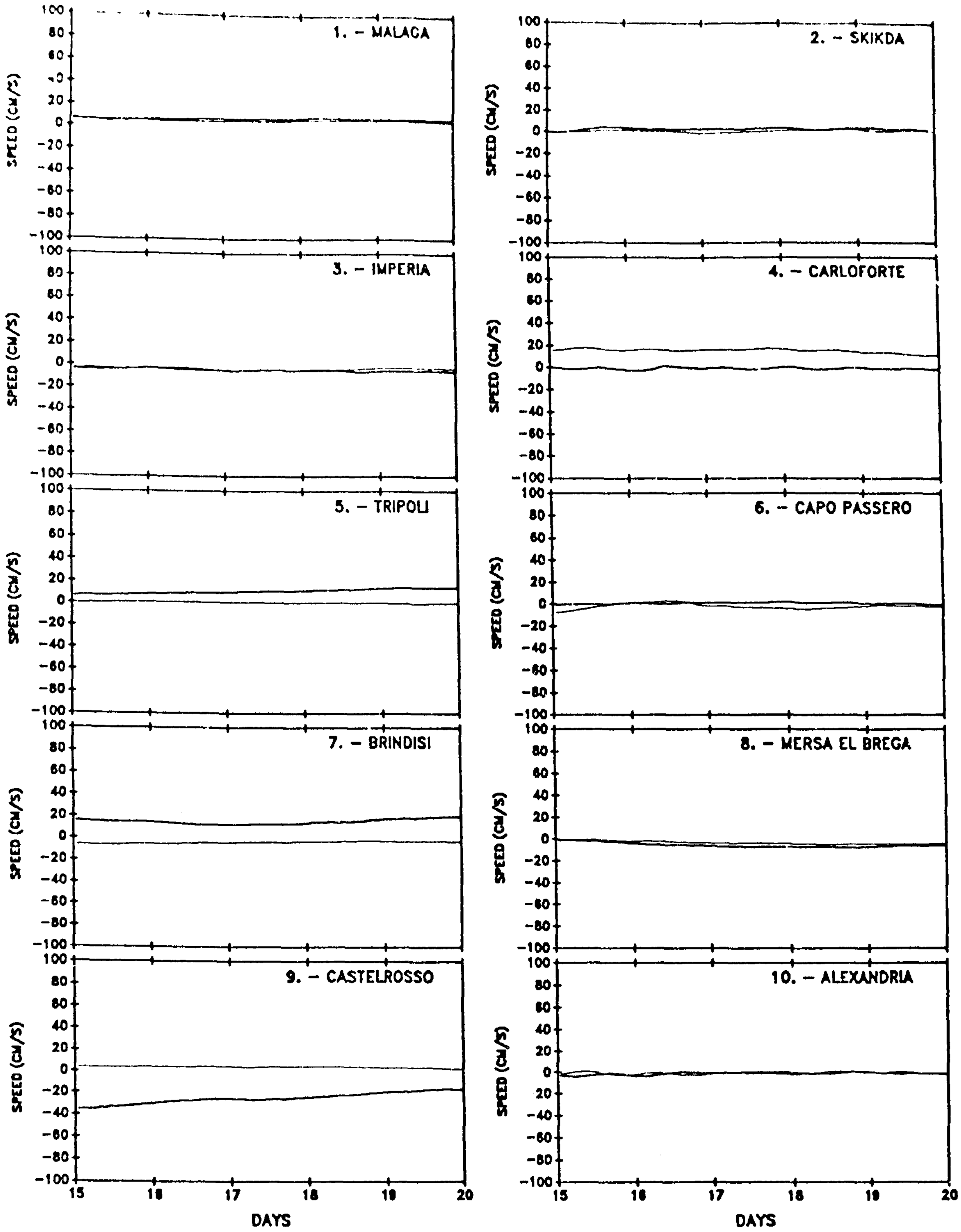

Fig. 6. Same as in Fig. 5. but for a simulation using a smoothed version of the bathymetry.

suggested that the model results would be much more realistic if we did not specify any vertical structure at the open boundary. Thus, we simply used the value at each layer given by (1).

Finally, we mention bottom boundary conditions in terms of friction. The Princeton model uses a logarithmic boundary layer formulation to calculate the quadratic bottom friction coefficient. A bottom roughness of 3 mm was used in the boundary layer formulation, and a minimum frictional coefficient of 2.5×10^{-3} was specified.

3. SIMULATIONS BASED ON CLIMATOLOGICAL T-S FIELDS

A five-day diagnostic simulation was performed driven only by the climatological T-S fields in order to determine if any unusual currents would be generated by the model. The simulation indicated a number of locations in the northern reaches of the western Mediterranean model domain where currents exceeded 2 m/s, with some as large as 2.75 m/s. These currents are not generated in a prognostic simulation using the model. They may have been a result of the sigma-coordinate system and the density gradients due to the horizontal and vertical interpolation of the original T-S data to the model grid.

A prognostic simulation for 20 days showed that the saltier water of the Mediterranean results in a vertical set-down of the surface of the water. The model indicates a drop of approximately 15 cm in the Mediterranean Sea relative to the Atlantic Ocean water outside the Strait of Gibraltar. We also considered current variations at the coastal stations indicated in Fig. 4. The currents (Fig. 5) at some stations have some significant variations. At Imperia (Station 3 in Fig. 4 with a grid cell depth of 217 m), current oscillations are persistent with about a 12 hr period and an amplitude of ~50 cm/s. At Capo Passero (Station 6, Fig. 4, with a grid cell depth of 26 m), the current oscillations are more erratic, with an amplitude as large as 50 cm/s. In the eastern Mediterranean, the north-south currents at Castelrosso (Station 9, Fig. 4, with a grid cell depth of 27 m) are also erratic, with a strong southward (offshore) flow. These patterns of current oscillations were not seen in the diagnostic simulation, so they must be triggered by internal modes.

These results indicate processes that are capable of triggering strong internal modes within several regions in the Mediterranean Sea. Such modes can be important with respect to the mixing of the water column, vertical shear responsible for the lifting of sediments off the ocean bottom, and the propagation of acoustic energy. Also, it is important to know if such modes have signals near tidal periods so that we may interpret actual current variations better.

It is possible that these internal modes are a result of the interaction of the climatological T-S structure and the bathymetry of model. However, we cannot rule out the possibility that the internal modes are being generated as a result of the application of sigma-coordinates over too steep of a bathymetry. This possibility is brought up by the fact that Imperia (Station 3) is in the region of the relatively large currents (> 2 m/s) generated when the model is run in the diagnostic mode. In addition, when tidal forcing is added, diagnostic simulations show that currents at Castelrosso (Station 9) become as large as 6-7 m/s. Because of these factors, we have to consider the possibility that the relatively strong currents seen in Fig. 5 may be an artifact of the numerical scheme, the grid, and the bathymetry.

The developers of the Princeton ocean model have provided a pre-processor to generate the needed input files to run the model for a given region. The computer code of the pre-processor has a smoothing routine for the bathymetry. The smoother always constrains the change in depth between adjacent grid cells to less than 50%. For example, if one grid cell has a depth of 100 m, adjacent grid cells can never have depths greater than 150 m. This smoothing routine was used on the Mediterranean Sea bathymetry, and the 20-day prognostic simulation was repeated. The resulting currents are shown in Fig. 6. The higher frequency current oscillations no longer exist. If the fluctuations had not been eliminated, we could be fairly certain that they were not a product of using sigma-coordinates over too steep a bathymetry. However, our results are inconclusive in that the

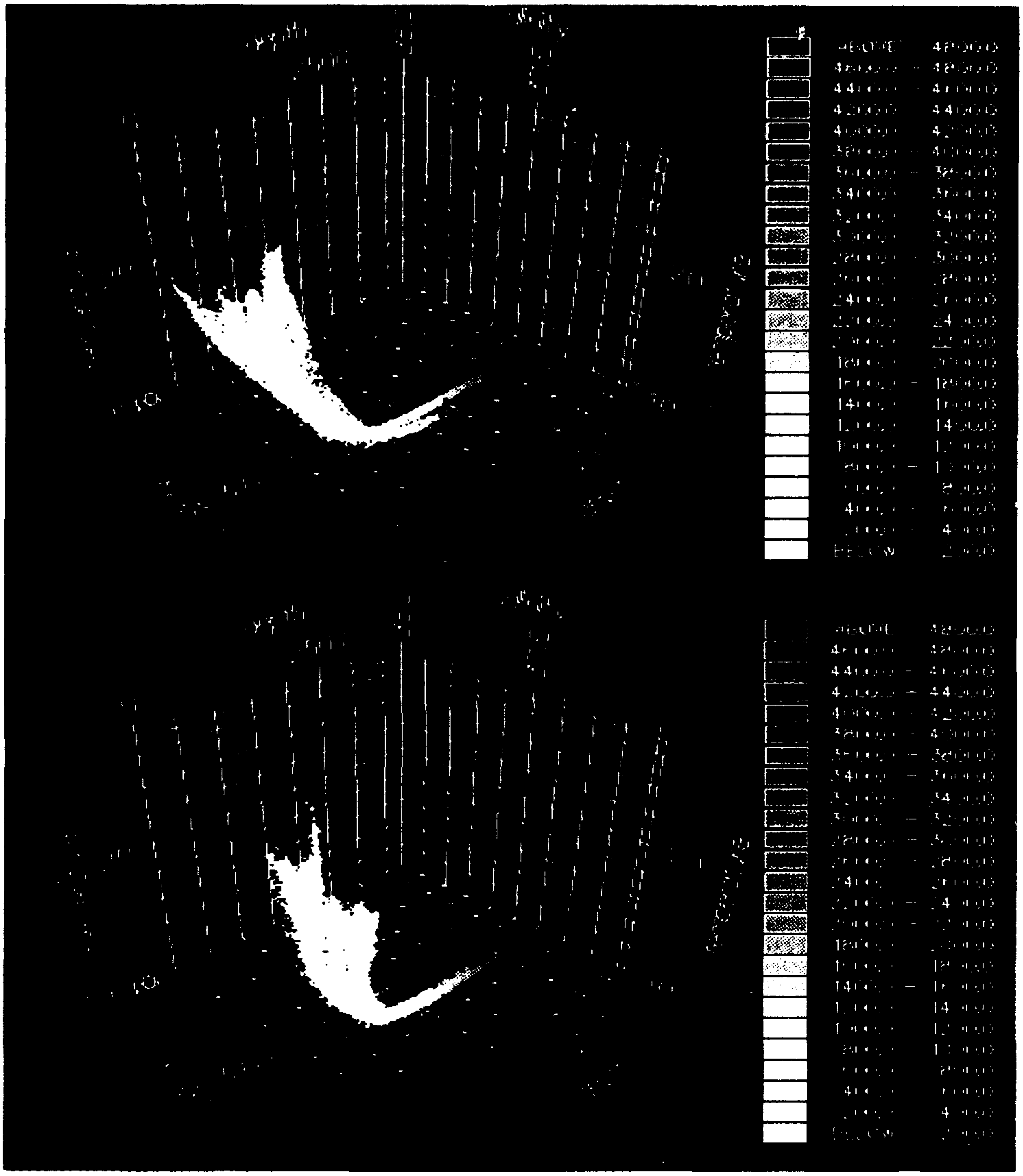

Fig. 7. Potential temperature and salinity relationships versus dept after 20 days of M_2 tidai forcing for the western (top) and eastern (bottom) Mediterranean Sea basins as divided by the Strait of Sicily.

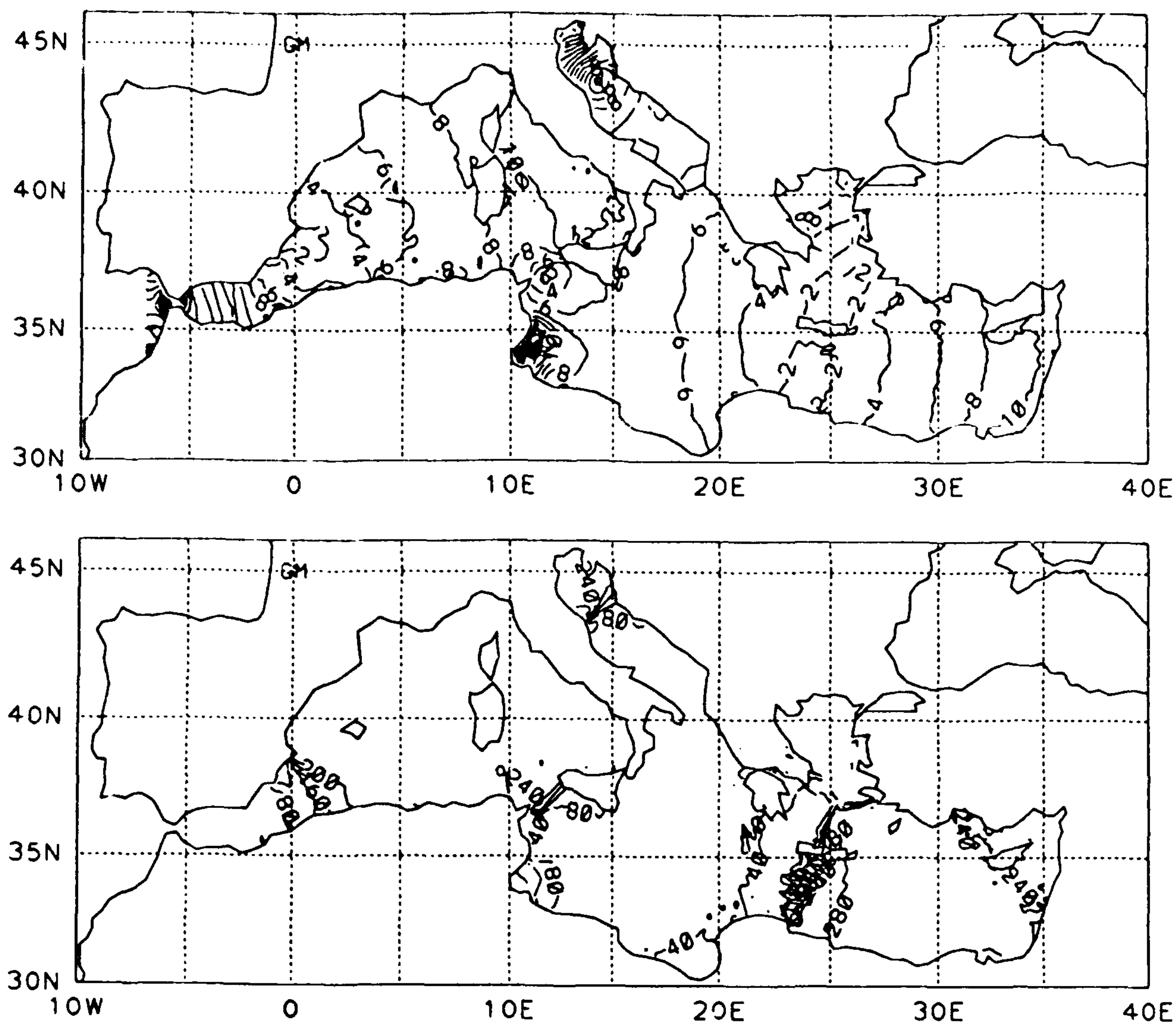

Fig. 8. Surface height amplitudes (cm) and phases (degrees relative to GMT) for the M_2 tide as predicted by the model.

bathymetric smoothing may have simply eliminated the slope characteristics that are responsible for the generation of the baroclinic modes as the climatological flow field moves over the shelf slopes in the model (Baines, 1982).

4. SIMULATIONS OF THE M_2 TIDE

The model was used to simulate the M_2 tides in the Mediterranean Sea. Driving for these simulations was provided by direct body forcing throughout the model domain as well as port forcing at the open western boundary. The body forcing was provided by the conversion of the tidal potential at each grid cell to an equivalent surface height anomaly (Reid and Whitaker, 1981). The spatial gradients of these potential surface heights were used in the momentum equations to provide direct gravitational forcing. Some tuning of the tidal potential phase (-15°) for the M_2 tide was performed to provide a good fit to the observed M_2 tides.

The boundary formulation used to force

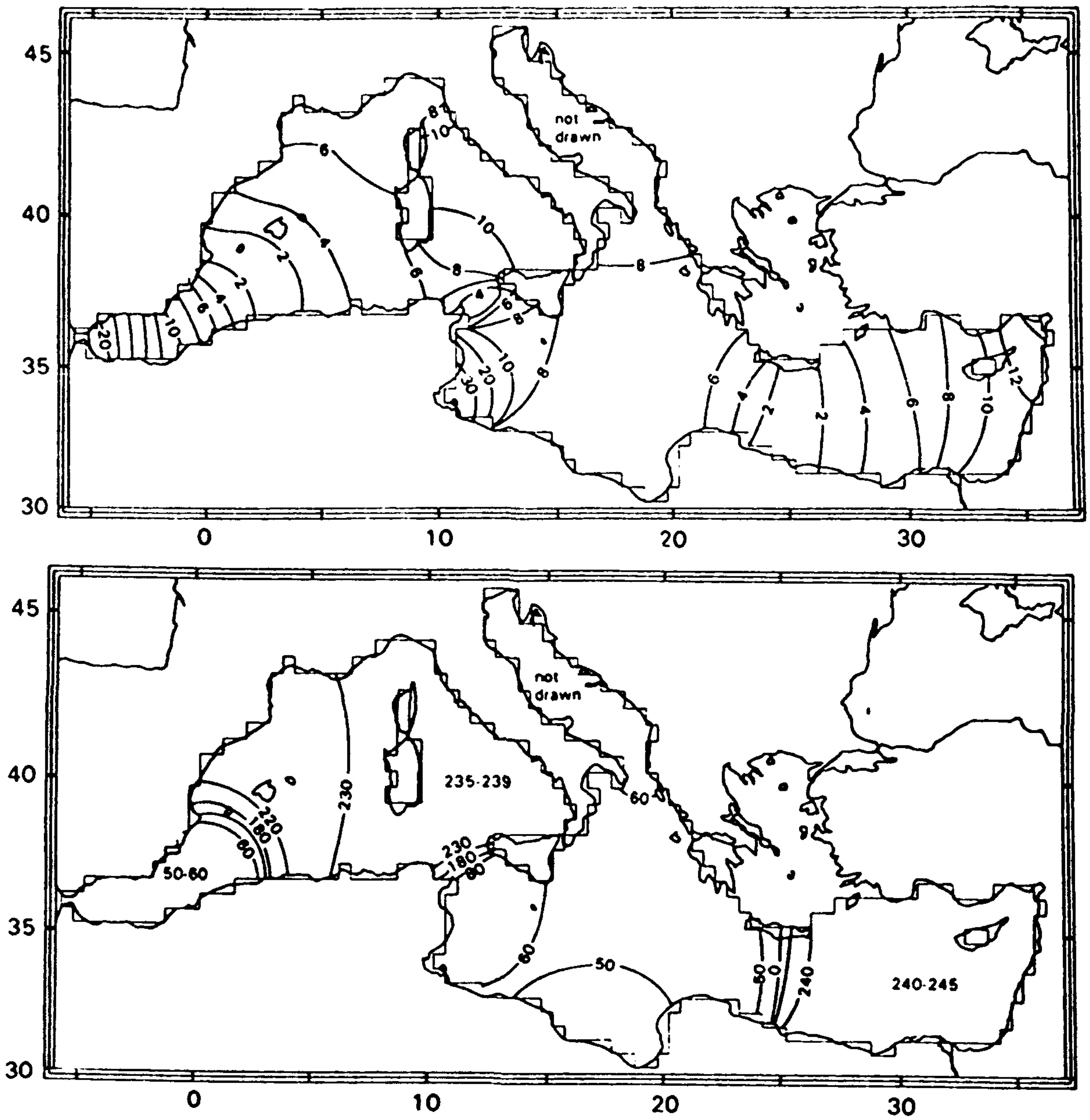

Fig. 9. Surface height amplitudes (cm) and phases (degrees relative to GMT) for the M_2 tide as predicted by a fit to all coastal observations (from Sanchez et al., 1992).

the tides at the western open boundary is an adaptation of the longwave radiation condition (Reid and Bodine, 1968). The vertically-averaged velocities at the boundary are given by

$$U = - (\eta - \eta_T) (g/D)^{\frac{1}{2}}$$

where η is the model-predicted surface height of the boundary grid cell and η_T is the time-varying tidal height obtained from the amplitudes and phases at the western boundary from a global tide model (Schwiderski, 1983). Some tuning of the η_T amplitudes and phases was required so that the model predictions at the western boundary matched the

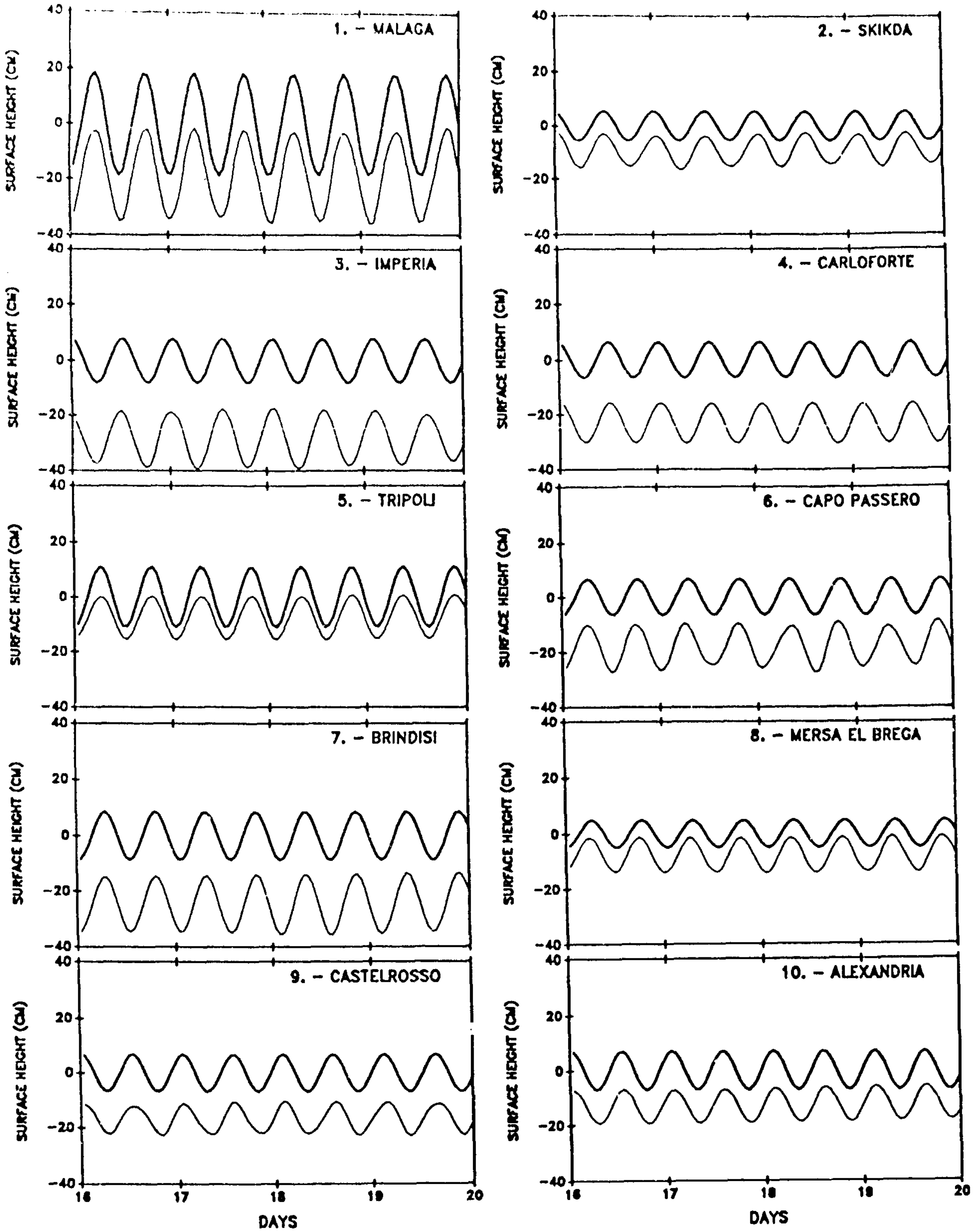

Fig. 10. Observed (darker line) and model-predicted (lighter line) surface height variations for the M_2 tide at stations indicated in Fig. 4. Observed tidal variations are relative to zero, and model-predicted variations are relative to the mean surface height as predicted by the model.

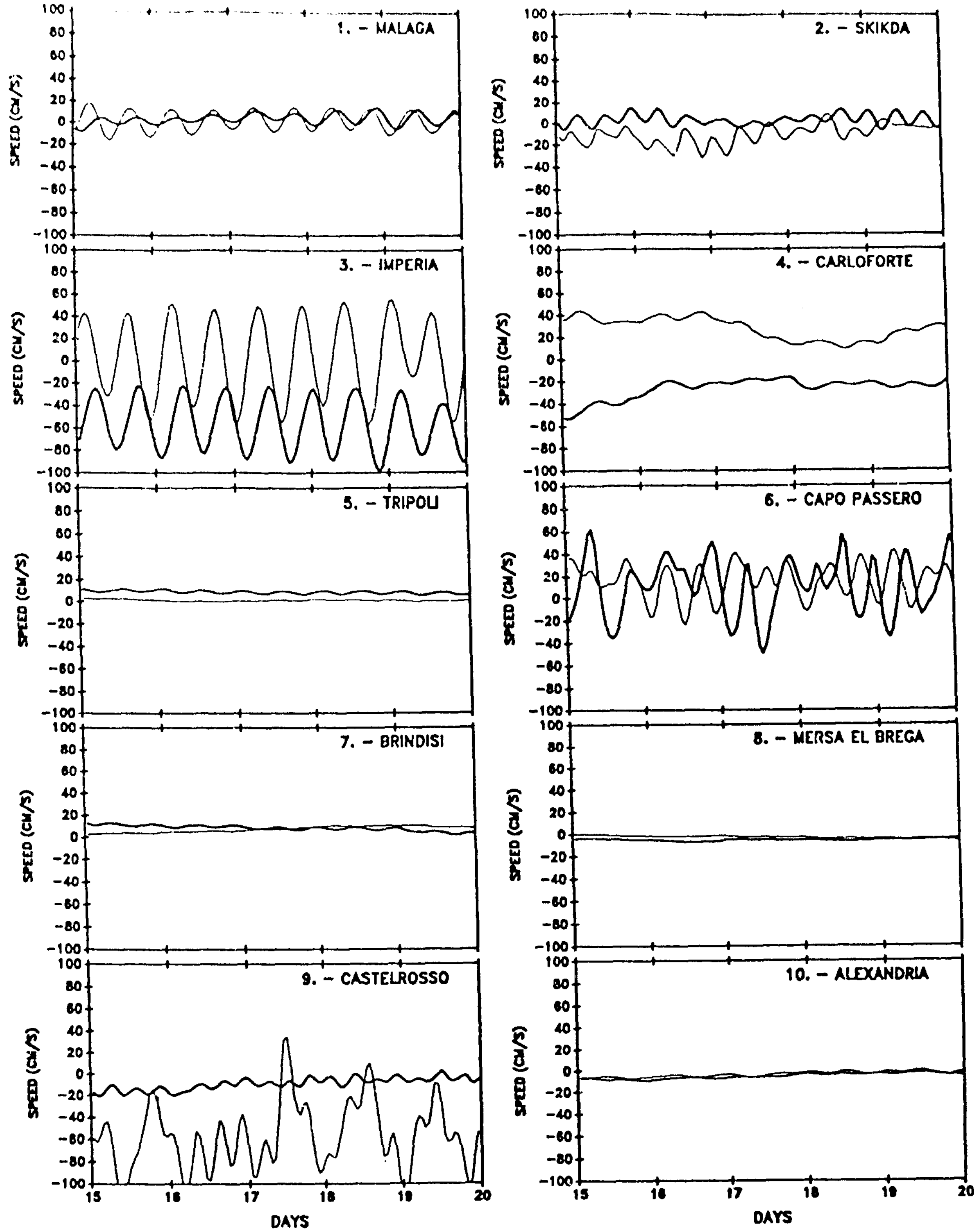

Fig. 11. Surface currents during the last 5 days of a 20 day prognostic simulation with tidal forcing. Darker lines are the x-directed currents, and lighter lines are the y-directed currents.

amplitudes and phases from the global tide model.

Our tidal simulations were performed with turbulent diffusion for salt and heat. The T-S relationships were modified somewhat (Fig. 7), but remained reasonable for 20 day simulations. However, we point out that the magnitude of the variations of the baroclinic currents will be underestimated. This is due to the fact that the climatological T-S field already represents a spatially and temporally averaged density structure, and this pycnocline will be further diffused away with time during a simulation.

Barotropic Tides

The model-predicted surface height amplitudes and phases are shown in Fig. 8. Maximum amplitudes are seen to occur in the Strait of Gibraltar, the northern Adriatic Sea, and the north-central coast of Africa just south of the Strait of Sicily. Maximum variations of phase occur at about the 0° meridian, the Strait of Sicily, the northern Adriatic Sea, and about 24° east longitude.

The results in Fig. 8 can be compared to the amplitudes and phases as predicted by a fit to all coastal observations shown in Fig. 9 (Sanchez et al., 1992). The agreement is good, and the individual station comparisons (Fig. 10) are quite favorable.

The M_2 surface height comparisons shown in Fig. 10 are plotted such that the observed tidal variations are relative to zero while the model-predicted variations are relative to the mean surface height as predicted by the model. The results indicate that most of the Mediterranean Sea has an average surface height setdown, with the exception of the northern coast of Africa and the far eastern Mediterranean.

Current variations at the coastal stations indicated in Fig. 4 are shown in Fig. 11. Once again, these are currents for the last 5 days of a 20-day simulation with turbulent diffusion for salt and heat turned on. These currents can be compared with the non-tidal coastal current variations shown in Fig. 5. For the most part, the model indicates that tidal variations contribute little to the overall flow field variations resulting from the climatological T-S field and the model bathymetry.

Candela et al. (1990) provided an in-depth analysis of observed surface and current amplitudes and phases for the M_2 tide in the Strait of Gibraltar. Their M_2 cotidal chart for the surface height is reproduced in Fig. 12. Their analysis shows a gradual west-to-east reduction in amplitude from ~70 cm to about 30 cm. The phase was observed to increase from north to south, from about 45° to 65°. Our corresponding model results (Fig. 13) show an west-to-east amplitude reduction of about 65 cm to 25 cm with a north-to-south phase increase of about 50° to 65°. I general, the model results agree well with t observations.

Candela et al. (1990) also analyzed current observations for the M_2 tidal ellipses over the sill leading into the Mediterranean Sea. The semimajor axis (essentially east-west) amplitudes and phases are shown in Fig. 14. The observations indicate phases increasing upward from 130° to beyond 150°. The amplitudes also increase as depth decreases, with minimum current amplitudes of about 60 cm/s to maximum amplitudes greater than 100 cm/s.

The observations can be compared with the model-predicted x-directed M_2 tidal amplitudes and phases at the shallowest north-south transect across the Gibraltar region represented in the model (approximately 5.8°W). These are shown in Fig. 15. Although the phases are close to the observations, the amplitudes are 50% too small. The reason for the discrepancies between the observed and predicted amplitudes is indicated in Figs. 14 and 15. The actual maximum sill depth (Fig. 14) is only about 300 m; but the grid-cell averaged depth at the sill location in the model bathymetry is ~316 m. In fact, the area across the Strait of Gibraltar in the model is about two times too large, and this results in predicted tidal amplitudes that are about two times too small.

As mentioned previously, the DBDB2 bathymetry from which the model bathymetry was developed is based on depth contours at 200 m intervals. As a result, there is no 300 m contour, and the DBDB2 bathymetry has north-south transects around the Strait of Gibraltar sill with maximum depths of 530 m (5.8°W) and 580 m (5.6°W). Thus, the grid cell average depth of our model for the same region will always be far too deep.

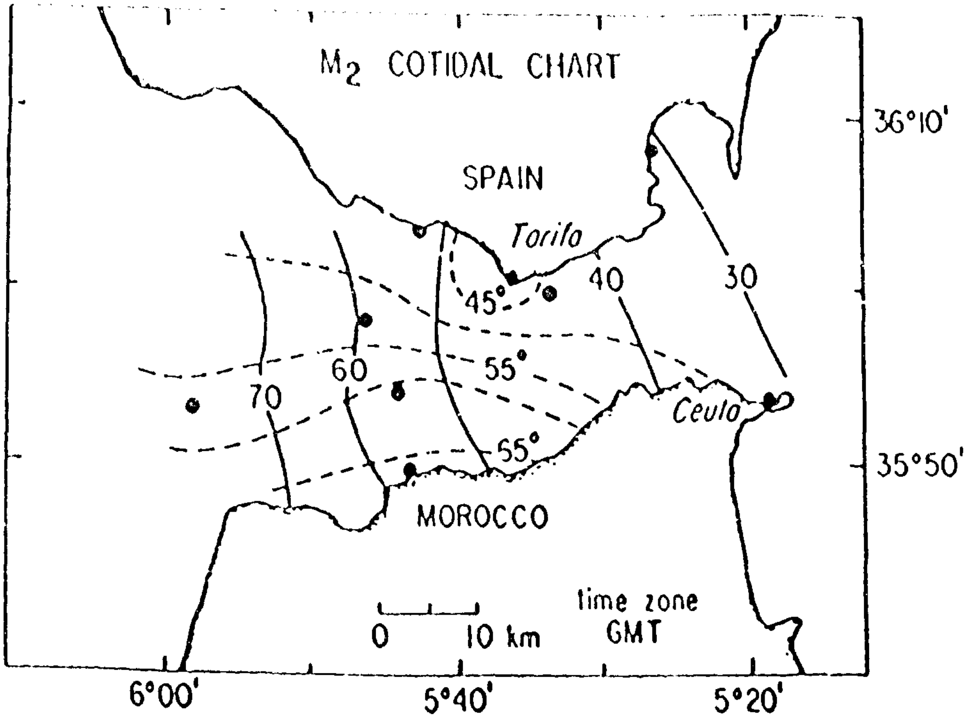

Fig. 12. Cotidal chart for the surface height for the M_2 tide based on observations (Candela et al., 1990).

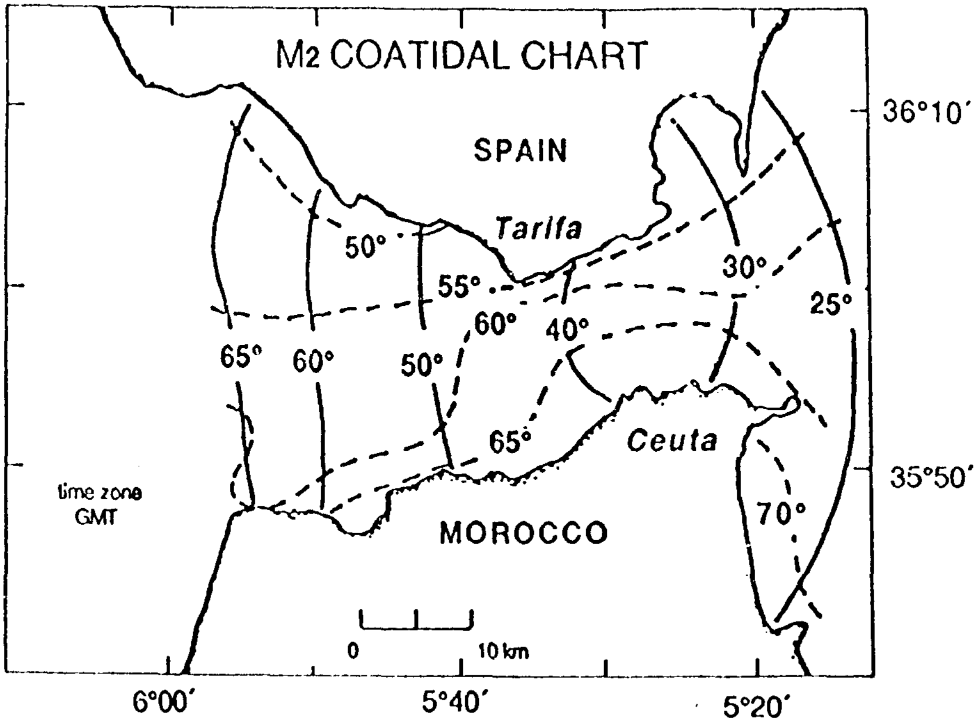

Fig. 13. Cotidal chart for the surface height for the M_2 tide as predicted by the model.

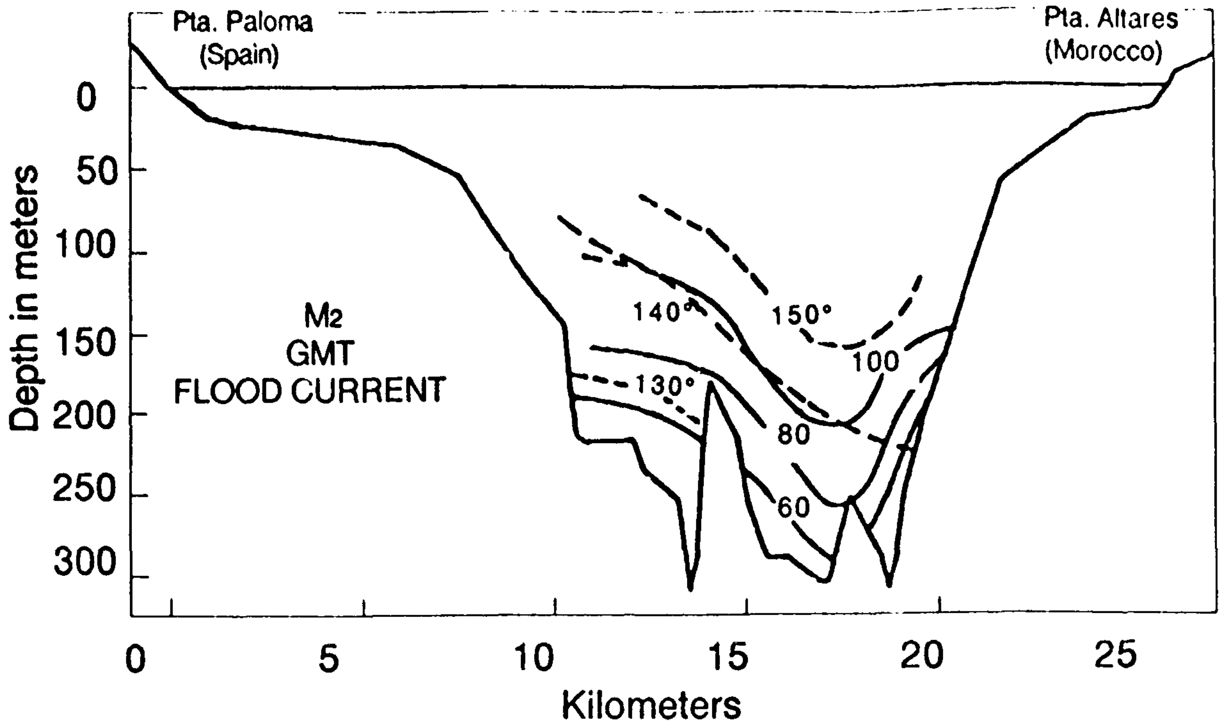

Fig. 14. Semimajor axis amplitude (cm/s) and phase (degrees relative to GMT) for the M_2 tide at the Strait of Gibraltar's shallowest sill (~5.75°W) (from Candela et al., 1990). North is on the LHS of the figure.

5. SUMMARY AND CONCLUSIONS

A fine resolution model has been developed for the Mediterranean Sea, and some initial simulations with the model have been presented. Even though the model uses a sigma-coordinate system in the vertical, the bathymetry was not smoothed in most of our simulations. This allows for a better prediction of baroclinic currents generated over the shelf slope as well as a better delineation of phenomena which may be influenced by the location of the shelf break (e.g., inertial oscillations).

The model maintains a reasonable approximation of the Mediterranean T-S relationship. In terms of tidal forcing, the model appears to be relatively skilled at predicting the barotropic M_2 tides in deep water and coastal stations. This is in spite of the fact that the model bathymetry is based on a data base which has limited information in coastal regions.

However, our comparisons with observed tidal currents point out distinct problems associated with the bathymetry data base. It is recommended that the NAVOCEANO 200 m interval bathymetry data base be upgraded to include depth contours at 10, 20, 50, 100, 300, 500, 700, and 900 m.

Simulations driven only by the climatological T-S fields indicate strong internal modes within several regions in the Mediterranean Sea. Since such modes can be important with respect to a number of processes, it is important to characterize and understand their nature and forcing. Unfortunately, we are unable to assure that the model-predicted internal modes are not a result of a problem of the application of sigma-coordinates over too steep a bathymetry. Additional simulations need to be performed using a z-level vertical coordinate system, the model bathymetry, and the climatological T-S fields. Such simulations would provide the evidence required to determine if the internal modes shown in our simulations are indeed real.

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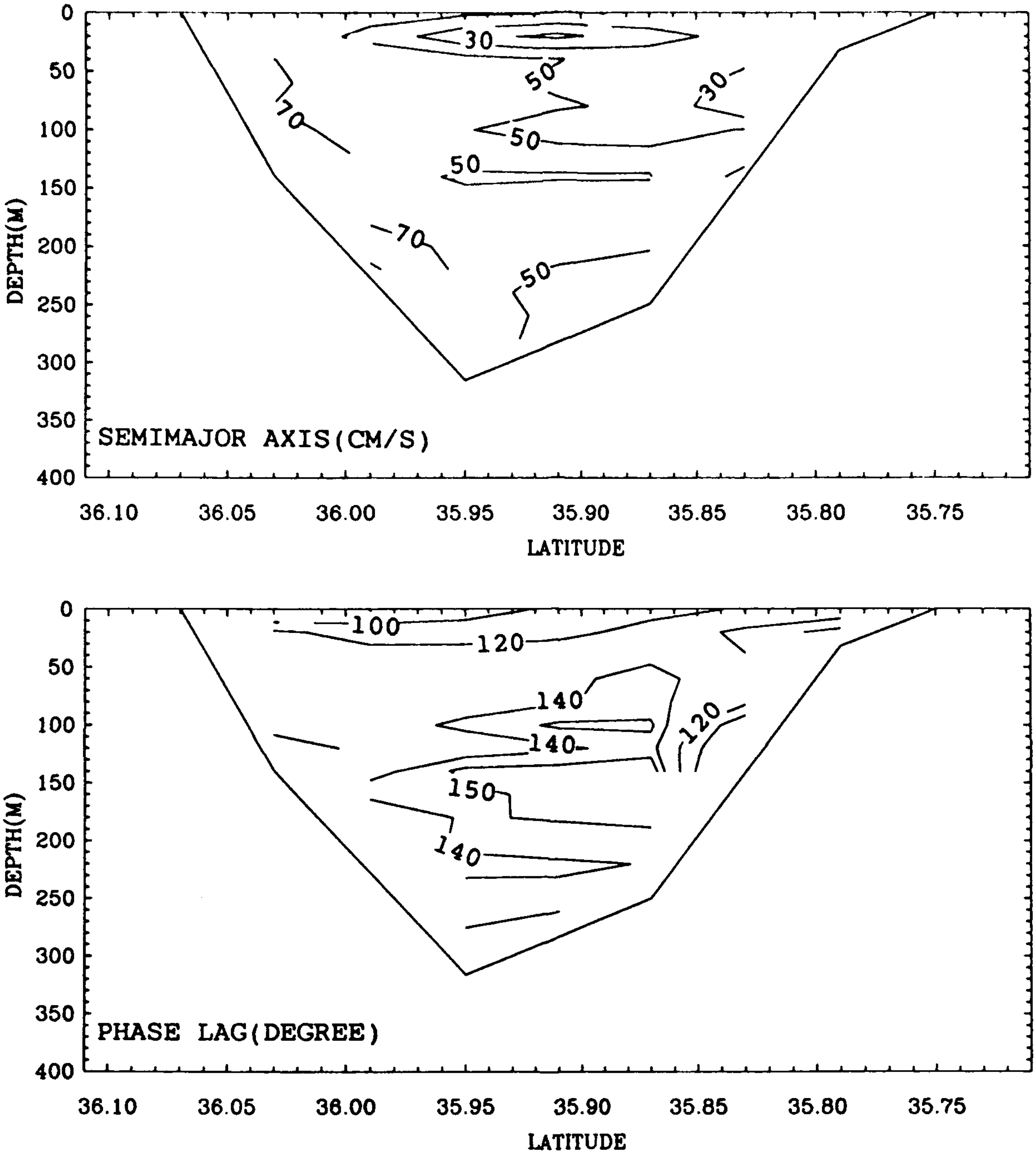

Fig. 15. Model-predicted x-directed amplitude (cm/s) and phase (degrees relative to GMT) for the M_2 tide at the model transect that best represents the Strait of Gibraltar shallowest sill (~5.75°W).

REFERENCES

Akima, H., 1978: A method of bivariate interpolation and smooth surface fitting for irregularly distributed data points. *ACM Trans. on Math. Software*, 4, 148-159.

Baines, P. G., 1982: On internal tide generation models. *Deep Sea Res.*, 29, 307-338.

Blumberg, A. F., and G. L. Mellor, 1987: A description of a three-dimensional coastal ocean circulation model. *Three Dimensional Coastal Models*, Coastal and Estuarine Sciences, 4, N. S. Heaps (ed.), Amer. Geophys. Union Geophysical Monograph Board, 1-16.

Camerlengo, A. L., and J. J. O'Brien, 1980: Open boundary conditions in rotating fluids. *J. Comput. Phys.*, 35, 12-35.

Candela, J., C. Winant, and A. Ruiz, 1990: Tides in the Strait of Gilbraltar. *J. Geophys. Res.*, 95(C5), 7313-7335.

Haney, R. L., 1991: On the pressure gradient force over steep topography in sigma coordinate ocean models. *J. Phys. Oceanogra.*, 21, 4, 610-619.

Levitus, S., 1982: Climatological atlas of the world ocean. NOAA Professional Paper 13, U.S. Govt. Printing Off., Wash. D.C., 173 pp.

Mellor, G. L., and T. Yamada, 1982: A hierarchy of turbulence closure models for planetary boundary layers. *J. Atmos. Sci.*, 31, 1791-1896.

Reid, R. O., and B. R. Bodine, 1968: Numerical model for storm surges in Galveston Bay. ASCE, *J. Water. and Harb. Div.*, 94, 33-57.

Reid, R. O., and R. E. Whitaker, 1981: Numerical model for astronomical tides in the Gulf of Mexico. Rpt. to the U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Miss. Dept. of Oceanogra., Texas A&M Univ., 115 pp.

Sanchez, B. V., R. D. Ray, and D. E. Cartwrite, 1992: A Proudman function expansion of the M_2 tide in the Mediterranean Sea from satellite altimetry and coastal gauges. *J. Oceanogica Acta*, 15, 325-337.

Smagorinsky, J., 1963: General circulation experiments with the primitive equations, I. The basic experiment. *Mon. Wea. Rev.*, 91, 99-164.

Schwiderski, E. W., 1983: Atlas of ocean tidal charts and maps, Part I: the semidiurnal principal lunar tide (M_2). *Mar. Geodesy*, Vol. 6, 219-265.

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13. Abstract *(Maximum 200 words).* Simulations have been performed using a primitive equation, sigma-coordinate, hydrodynamic model of the Mediterranean Sea. The model uses a climatological temperature-salinity field on a grid with a spacing of 5-12 km in the horizontal. Simulations indicate that the model does a good job in reproducing the surface height amplitude and phase of the M_2 tide. The semi-major axes of the model M_2 current ellipses in the Strait of Gibraltar were approximately 50% smaller than the observed current ellipses. This is a result of the data base used to generate the model bathymetry, which has depths in the vicinity of the sill of the Strait of Gibraltar (~300 m) which are about two times too deep (~550 m).

Additional simulations show current fluctuations that may be the result of a) the interaction of the climatological density field with the model bathymetry to trigger strong baroclinic modes or b) problems associated with the application of sigma-coordinates over steep bathymetry. When the model bathymetry was smoothed, the current fluctuations were eliminated. However, it is unclear if the smoothing eliminated a bathymetry/sigma-coordinate problem or simply eliminated the shelf slopes and breaks which are responsible for the generation of the baroclinic currents.

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